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# Reframing energy security in the clean energy transition under cross-border risks and solutions

Stephanie Moura *, Fatemeh Rostami, Paul Deane, Hannah Daly, Vahid Aryanpur

*Sustainability Institute, School of Engineering and Architecture, University College Cork, Ellen Hutchins Building, 6 Lee Rd, Sunday's Well, Cork, Ireland*

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ABSTRACT

As energy systems transition to clean energy, energy security is undergoing a fundamental transformation. Although changing geopolitical dynamics and market volatility have drawn greater attention to cross-border risks, the literature does not clearly establish how the solution to these risks varies across different energy systems. Moreover, import dependence continues to be treated predominantly as a vulnerability, despite growing recognition that, in certain contexts, interdependence in international investment and trade can enhance energy reliability and affordability. This review addresses these conceptual ambiguities by consolidating existing scholarship and examining how the framing of energy security has evolved. This is achieved through two analytical approaches: a bibliometric analysis of energy security research over the past 45 years and a systematic qualitative review of 65 selected studies. The findings highlight three main trends. First, energy security has evolved from a narrow focus on traditional energy carriers towards a broader framework encompassing geopolitical, financial, and technological cross-border risks. Second, the growing role of China in energy security research and global supply chains highlights a shift towards state-coordinated approaches, contrasting with the market-based approaches prominent in Western studies. Third, technology choices, the pace of the energy transition, and supply-demand trade-offs limit the effectiveness of traditional responses to cross-border risks. The study therefore reframes energy security in the clean energy transition as the governance of cross-border interdependence, highlighting the need for context-specific strategies that balance the benefits of international interdependence with the vulnerabilities it creates.

## 1. Introduction

Energy security is a polysemic concept that has attracted scholarly attention over the decades [1]. The International Energy Agency (IEA) defines energy security as the reliable and affordable supply of energy [1,2], yet the practical meaning of "reliability" and "affordability" varies considerably across energy systems and national contexts. Compounding this difficulty, energy security is rarely pursued as a standalone goal. It is one of three interdependent dimensions of the energy trilemma, alongside energy equity and environmental sustainability, with policies that strengthen one dimension often affecting the other two [3–6]. Energy systems are inherently complex socio-technical configurations, shaped by local resource endowments, infrastructure development, regulatory frameworks, and geopolitical exposure [7]. As a result, there is no single pathway to ensuring reliability and affordability, as energy security is contingent upon structural conditions and evolving risk profiles.

Reflecting this heterogeneity, recent scholarship has moved away from universal energy security definitions toward more context-sensitive frameworks [8,9]. This shift is not coincidental but is closely linked to the nature of the energy transition, which is frequently characterised in the literature as a "messy" and non-linear process [10]. The transition to a carbon-neutral economy remains uneven across regions and sectors, creating new trade interdependencies as existing ones decline. Countries, including developed economies, remain at different stages of decarbonisation, with many still substantially reliant on fossil fuels [10]. Accordingly, this review treats the transition as ongoing rather than an accomplished reality.

Building on this uneven context of the energy transition, this study adopts a vulnerability-based definition of energy security, conceptualising it as the minimisation of energy system vulnerability and avoiding a general definition of what vulnerability is. Influential work in

* Corresponding author.
*E-mail addresses:* stephanie.moura@ucc.ie (S. Moura), frostami@ucc.ie (F. Rostami), jp.deane@ucc.ie (P. Deane), h.daly@ucc.ie (H. Daly), vahid.aryanpur@ucc.ie (V. Aryanpur).

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this area identifies context-based vulnerability along two key dimensions: the exposure of energy systems to risks and their inherent resilience in coping with these risks [11]. This perspective allows for a system-specific understanding of energy security, particularly relevant in the context of the uncertainties introduced by the clean energy transition. This rejects the assumption that import dependence or trade interdependence inherently increase exposure and undermine energy security. Their effects are instead treated as context-dependent. Import dependence may heighten exposure in one system while supporting diversification and resilience in another [12]. Thus, its net effect on vulnerability, and thus energy security, depends on the energy system context.

By focusing on context-based vulnerabilities, this review distinguishes itself from studies that rely on more generic, indicator-based frameworks [13,14]. Rather than comparing countries through standardised indicators, we examine the specific conditions under which vulnerabilities emerge. We build on recent reviews that identify and examine vulnerabilities emerging specifically from the energy transition [15–17]. Beyond these existing review contributions, the present study focuses on highlighting cross-border risks and interdependencies (e.g., mutual reliance between national energy systems arising from trade, shared infrastructure, or technological supply chains) and demonstrates how these factors increasingly shape energy security strategies in the clean energy transition.

Therefore, to clarify the current state of knowledge, this review is structured around three main research questions (RQs): (1) How has the framing of energy security evolved in the context of the clean energy transition? (2) Which cross-border risks are most prominent in the existing literature? (3) Which energy security strategies appear most effective in addressing these risks? To address these questions, the review combines two complementary analytical approaches. First, to answer RQ1, a bibliometric analysis of approximately 10,000 studies is conducted to identify key themes, trends, and the evolution of energy security discourse. Second, the insights gained from the bibliometric analysis are used to construct a targeted set of keywords that guide a systematic qualitative review addressing RQ2 and RQ3. Applying defined inclusion and exclusion criteria yields a final sample of 55 studies selected for detailed examination. These studies are analysed comparatively to identify the dominant cross-border risks and to assess the range of energy security strategies deployed across different national and regional energy systems, highlighting both common challenges and context-specific adaptations.

**Table 1**
Search strategy and final sample of the bibliometric analysis.

| Search | Search string | Studies retrieved | Publication years |
|---|---|---|---|
| **1** | "energy security" | 9624 | 1980-2024 |
| **2** | "energy security" AND "energy system*" | 1017 | 1985-2024 |

## 2. Method

The review comprises two stages: a bibliometric analysis to map the field and its thematic evolution over 45 years, followed by a systematic review of the main themes identified.

### 2.1. Bibliometric analysis

A bibliometric analysis was performed in June 2025 in the Scopus database using two different search strategies, as detailed in Table 1. Search 1 identified publications containing the keyword in titles or abstracts, limited to English-language, peer-reviewed studies through 2024. Search 2 narrowed the scope by combining the two terms under the same filters.

Using the VOSviewer software, co-occurrence network maps were generated for both searches based on the most frequently occurring terms. This is an approach commonly used in the literature [18,19] and it is well suited to answer RQ1, since it shows what "energy security" is discussed alongside, rather than simply how often the terms appear in the documents.

To enhance the quality and interpretability of the co-occurrence network, synonym terms were merged (e.g., "United States" and "USA"), and generic research-related words were excluded (e.g., "insight" or "example"). In addition, to improve visualisation, terms related to central topics, such as the role of critical minerals, were grouped (e.g., "metal," "mineral," "material," or "raw material"). Clusters were defined by setting a minimum term occurrence threshold proportional to the sample size and requiring at least three thematic clusters to facilitate comparison. Cluster analysis and naming were conducted independently by two researchers.

The two searches are complementary. Search 1 captures the broad evolution of energy security discourse across disciplinary and application contexts, including geopolitical, economic, environmental, and other framings, providing the wider conceptual landscape over time. Search 2 narrows the focus to energy-systems research, providing the system-level insights that inform the systematic review keywords and vulnerability-based conceptual framework underpinning the review protocol.

### 2.2. Systematic literature review

Table 2 presents the search string, filters, inclusion, and exclusion criteria for the systematic review. The keywords aim to capture the key themes identified in the Search 2 bibliometric analysis, focusing on energy security within energy systems and commonly used indicators. The inclusion/exclusion criteria were guided by the vulnerability approach developed by two of the most influential authors identified in Search 2 (see Table S6) [11].

Vulnerability reflects the balance between exposure and resilience. Exposure captures factors that expose energy systems to risk, such as import dependence and supplier instability, while resilience captures their capacity to respond, such as energy-source and trade-partner diversification [20]. Applying these criteria did not assume in advance how a system's combination of exposure and resilience translates into overall vulnerability. High exposure may still result in low vulnerability

**Table 2**
Protocols of the systematic literature review.

| | |
|---|---|
| Search string | "energy security" OR "security of" AND "energy system*" AND ("model*" OR "analy*" OR "measur*" OR "quant*") |
| **Filters** | "Energy security" in title; peer-reviewed journal articles, written in English |
| **Inclusion Criteria** | Studies that measure energy security in energy systems by conceptualising it as low vulnerability, where vulnerability is defined as a function of both exposure to risks and the energy systems' resilience [9], [11], [20]. |
| **Exclusion Criteria 1** | Studies that measure the resilience of energy systems but do not measure exposure to risk. |
| **Exclusion Criteria 2** | Studies that measure the exposure to risk in energy systems, but do not measure resilience. |
| **Exclusion Criteria 3** | Studies that do not measure exposure to risk or resilience. |
| **Exclusion Criteria 4** | Studies that use a dimension approach with a complex energy security index do not allow for an analysis of risk and resilience [9]. |

where resilience is high, and the extent to which resilience offsets exposure is specific to the energy system examined. Import dependence illustrates this well. While it introduces risk exposure, the literature also shows that it can strengthen resilience where accompanied by diversified suppliers or established trade relationships [21,22]. Vulnerability is therefore understood as the balance between exposure and resilience, rather than either dimension alone, with both required to structure the assessment of vulnerability.

The main search was conducted in June 2025 using the Scopus and Web of Science databases. Two researchers independently screened studies at each stage, recording exclusion/inclusion criteria and key study characteristics in a structured table. Studies were retained if they contributed meaningfully to understanding energy security, clearly described their methodology and treatment of risk exposure and resilience, provided a sound analysis, and addressed at least one research question. Eleven ambiguous cases were resolved through joint discussion. Consistent with systematic review guidance [23], criteria were applied to support a defensible assessment aligned with the review objectives, rather than to identify methodologically flawless studies.

Fig. 1 illustrates the filtering process by each step. Backward snowballing of the selected 39 studies subsequently identified 16 additional relevant papers [24]. In August 2026, a supplementary country-specific search was conducted to address potential geographical gaps in the evidence base and increase the coverage of evidence from countries demonstrating comparatively strong energy-security performance. The country selection for this supplementary search was guided by Ref. [14], which provided a reference for identifying countries with strong energy-security performance. This was considered particularly relevant given the review's focus on the effectiveness of energy-security strategies, as including evidence from countries with strong energy-security performance strengthens the geographical and comparative coverage of the evidence base. The same predefined eligibility criteria were applied to the identified studies. Ten studies were considered relevant additions to the coverage of the selected countries, resulting in 65 studies in the final review.

## 3. Results and discussion

### 3.1. Bibliometric analysis

The bibliometric analysis is discussed in three periods: pre-2000 (119 documents), 2001-2015 up to the Paris Agreement (2823 documents), and the post-Paris Agreement 2016 to 2024 (6682 documents). Fig. 2 presents the main topics and clusters that emerged over time. Based on qualitative analysis of the terms, we identified three key themes within each cluster: Emissions & Environment, Market & Cost, and Supply & Risk.

The *Market & Cost* cluster shows the most substantial change over time. Before 2000, studies focused mainly on oil prices and the roles of OPEC and the IEA, reflected in terms such as “oil price,” “OPEC,” and “IEA.” Between 2001 and 2015, the cluster broadened to include biofuels and global warming concerns, with “biofuel,” “biodiesel,” and “sustainability”. From 2016 to 2024, renewable energy sources and energy technologies became more prominent. “Renewable energy,”

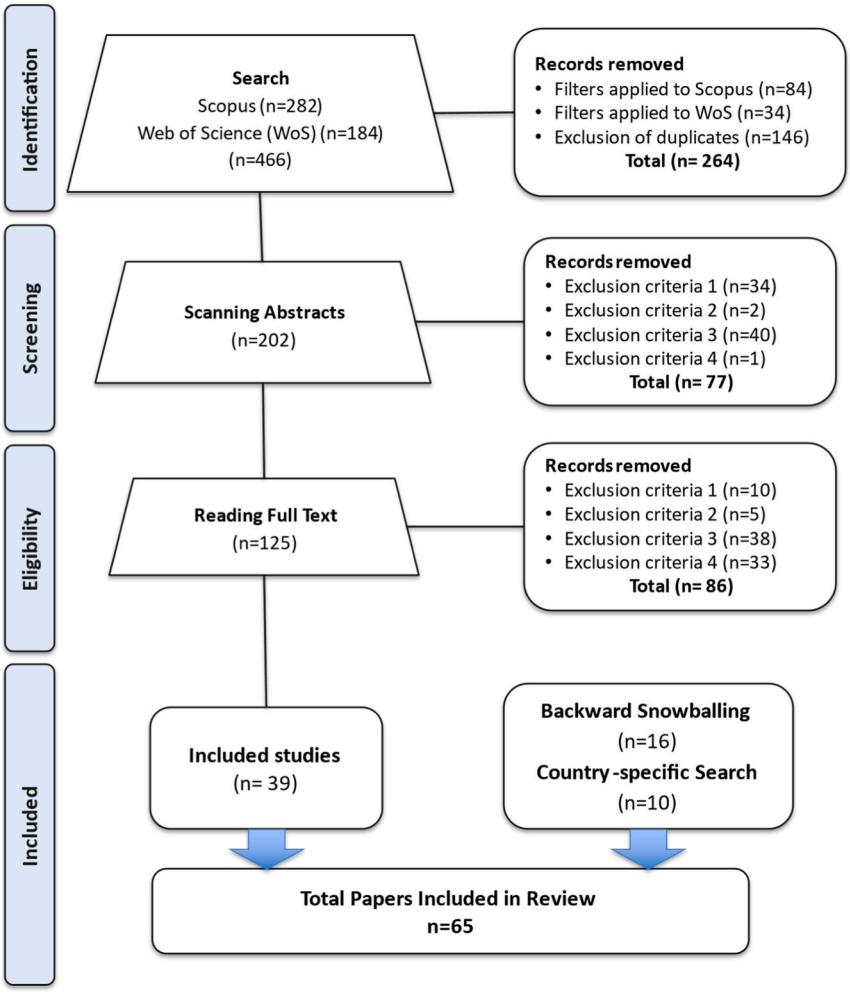


**Fig. 1.** Filtering process.

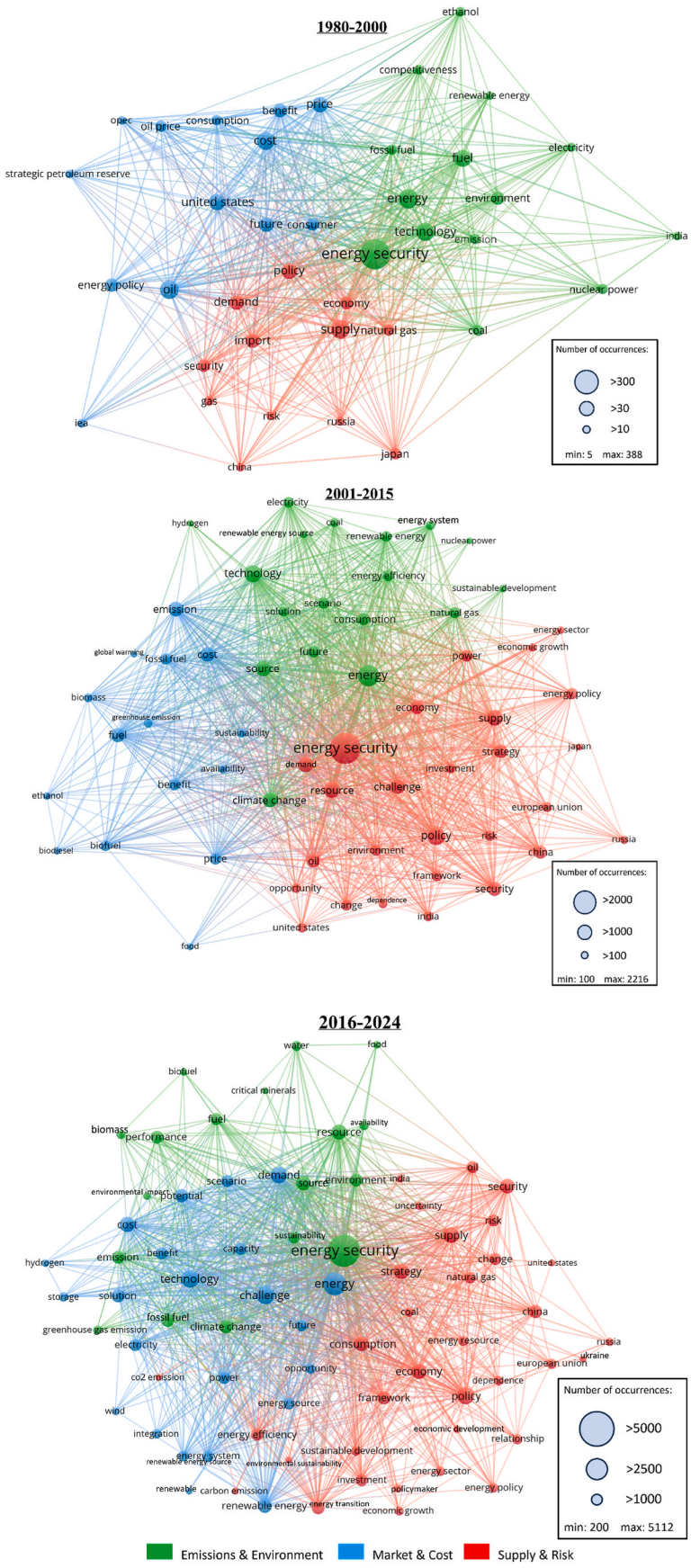


**Fig. 2.** Energy security in the literature (1980-2024).
*Notes*: The period 1980-2000 comprises 119 documents. The period 2001-2015 comprises 2823 documents, and the period 2016-2024 comprises 6682 documents. Figure generated using the software VOSviewer version 1.6.20.

"renewable energy source," and "storage" appeared in the cluster, alongside "integration," "hydrogen," and "wind."

In *Emissions & Environment*, early studies focused on environmental concerns and the competitiveness of low-carbon energy sources. Terms such as "environment" and "emission" appeared alongside "fuel" and "technology," while "nuclear power," "competitiveness," and "ethanol" reflected the focus on specific energy sources and their economic position. Nuclear power remained present in the 2001–2015 cluster, although with lower occurrence, and neither nuclear power nor coal appeared among the cluster terms after 2015. Instead, "critical minerals" and "environmental impact" emerged in 2016–2024, alongside the continued presence of "fossil fuel" and "technology." Overall, the cluster points to a changing focus from conventional energy sources, with the decline of nuclear power and coal, towards the environmental and material implications of the transition to renewables.

In *Supply & Risk*, discussions consistently address the geopolitics of energy supply and risk across key countries and regions. China (a major consumer), Russia (a major producer), and Japan (a major consumer) appear across all three periods, reflecting their sustained relevance. India (a major consumer), the United States (both a major producer and consumer), and the European Union (a major consumer) enter from 2001 to 2015 onward, but are absent before 2000, indicating a broadening geopolitical scope from the early 2000s. Ukraine appears only in 2016–2024, reflecting its growing relevance following the Russia–Ukraine war and its role in European energy supply and transit. A further shift concerns the framing of import-related risk. "Import" appears only before 2000, while "dependence" emerges from 2001 to 2015 and persists thereafter. This suggests a shift from viewing supply risk through the physical fact of energy imports towards a more structural framing centred on dependence, consistent with the vulnerability-based understanding of energy security in Section 1, where risk depends on the system's broader resilience rather than import volumes alone.

Energy security appears in the leading cluster in each period, reflecting its role as the main search term, but its predominant association changes over time. Before 2000, it ranks first within *Emissions & Environment*; in 2001–2015, within *Supply & Risk*; and in 2016–2024, again within *Emissions & Environment*, alongside terms such as "critical minerals" and "sustainability."

Another relevant shift in cluster association concerns specific fuels and technologies. Ethanol appears in *Emissions & Environment* before 2000, then moves to *Market & Cost* in 2001–2015 alongside "biodiesel" and "biofuel." Hydrogen is absent before 2000, appears in *Emissions & Environment* in 2001–2015, and moves to *Market & Cost* in 2016–2024, alongside "storage" and "integration." These shifts reflect the evolution of emerging fuels and technologies from early-stage development and exploration towards their integration and establishment within energy markets.

Fig. 3 illustrates the number of publications per year, the leading country of origin for those publications, and the cumulative total over time. Publications from 1980 to 1997, totalling 87 studies, were omitted from this plot due to missing or ambiguous information on country of origin. The US dominated the literature for most of the period, while publications from Chinese researchers increased markedly in recent years, from 12% in 2018 to 23% in 2024. This shift may reflect several factors, including China's large population and market scale, its central role in clean energy technology supply chains, and the growing policy relevance of energy security within a political agenda characterised by long-term planning and large-scale cross-border infrastructure investments, such as those pursued through the Belt and Road Initiative [10], [25–31]. These factors are suggestive rather than conclusive explanations for the observed trend.

Additional bibliometric results, including the most globally cited articles, most influential authors, country-level scientific production, and the full composition of each cluster, are provided in Supplementary Table S1–S4. Sovacool is the most cited author in this search (4299 citations across 62 articles; Supplementary Table S2), reflecting his broad influence on the field.

Fig. 4 shows the main thematic clusters from the "energy security" and "energy system" search, covering the full period 1985–2024 due to the smaller number of papers in earlier decades. While Fig. 2 traces how energy security is framed across the broader literature, this narrower search shows how it is operationalised in technical and system-level research, revealing additional insights through shifts in the underlying themes.

One cluster, labelled *Market & Environment*, shifts from cost-related issues towards the technical and environmental trade-offs of different technologies. Terms such as "capacity," "demand," and "environmental impact" capture these trade-offs, alongside system-level infrastructure and engineering terms such as "grid," "heat," and "power generation," which are absent from the broader energy security search.

A second cluster, *Emissions & Consumption*, places stronger emphasis on energy consumption and energy efficiency, dimensions less prominent in the broader energy security literature. Terms such as "share," "reduction," and "long term" appear here but not in the broader energy security search, likely reflecting this search's technical, systems-modelling orientation, in which consumption patterns, emissions-reduction targets, and long-term scenario horizons are treated as quantifiable modelling variables. Countries such as "China" and "India" appear here due to the focus on their decarbonisation strategies, the phase-out of "coal," and efforts to reduce dependence on "oil," "gas," and other fossil-fuel emissions in "long-term" "scenarios."

A third cluster, which we identify as *Supply & Security* (the largest cluster in this search), terms including "policy," "economy," "framework," and "sustainable development," also appear in the broader energy security search, reflecting the fact that energy security has always been discussed, at some level, in relation to governance and economic

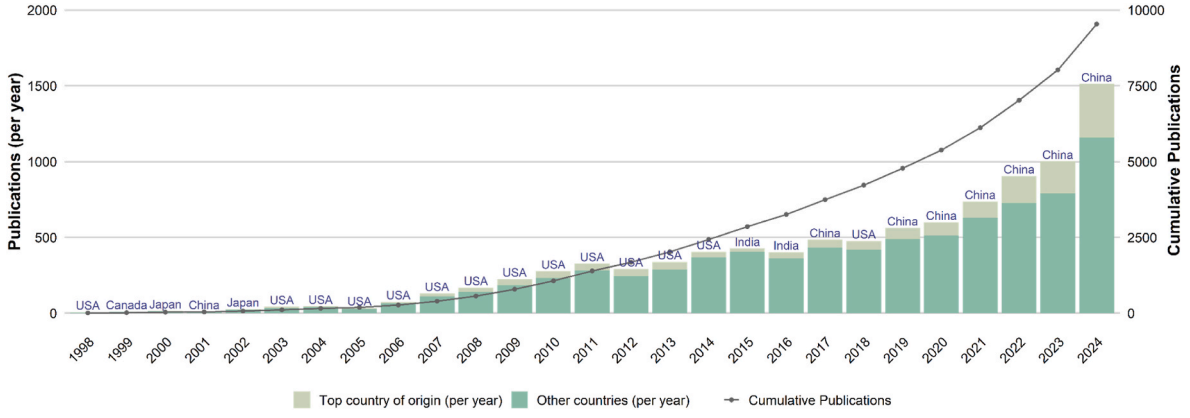


**Fig. 3.** Annual publications in energy security, top country of origin per year, and cumulative total over time.

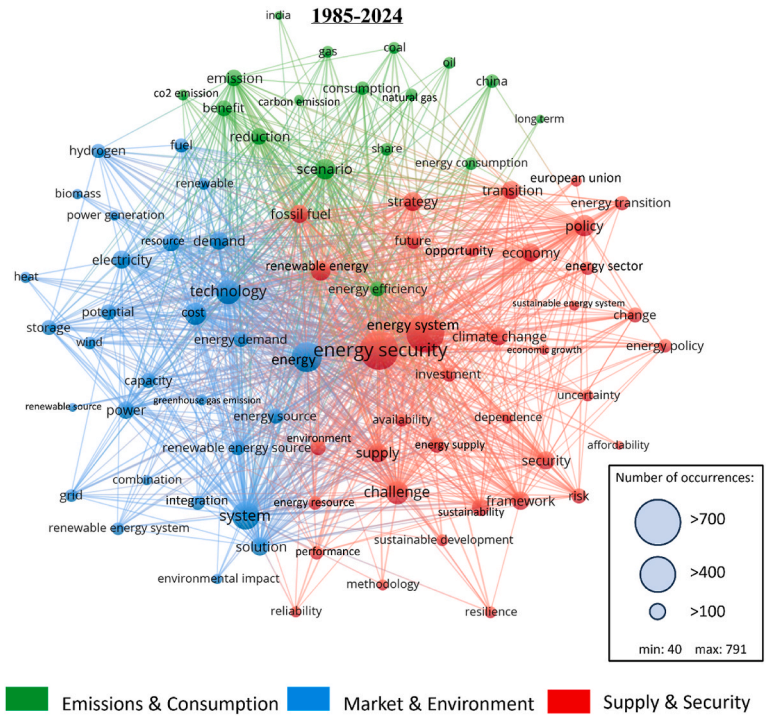


**Fig. 4.** Energy security in energy systems in the literature (1985-2024).
*Notes*: The period 1985-2024 comprises 1017 documents. Figure generated using the software VOSviewer version 1.6.20.

considerations, regardless of whether the literature engages with energy systems specifically. However, terms such as "resilience," "reliability," and "affordability" appear only in the narrower systems-focused search, suggesting that these dimensions become more visible when energy security is examined through the design, modelling, and operation of energy systems. The prominence of resilience and risk-exposure terms specifically within this system-level cluster provides bibliometric evidence in support of the vulnerability-based conceptualisation of energy security adopted throughout the systematic review addressing RQ2 and RQ3.

Fig. 5 illustrates the number of publications per year, the top country of origin of those publications per year, and the total cumulative number of publications. Before the year 2000, only five studies were captured by the search. However, their country-of-origin information was either not available or ambiguous. Looking at the trends in the existing data, it is possible to notice that there is an increase in the number of publications from the year 2009, and a more pronounced and steadier upward trend after the year 2017. In terms of cumulative numbers, after the year 2011, there is a steady upward trend. Countries of origin of these publications historically were dominated by different Western countries, and in more recent years, a dominance of Chinese studies is observed.

Additional bibliometric results, including the most globally cited articles, most influential authors, country-level scientific production, and the full composition of each cluster, are provided in Supplementary Table S4–S8. Cherp and Jewell rank jointly second among the most influential authors in this search (882 citations each; Supplementary Table S6), supporting the relevance of the vulnerability-based framework adopted in step 2 of this review.

### 3.2. *Systematic literature review*

Table 3 summarises the 65 studies reviewed in the final sample.

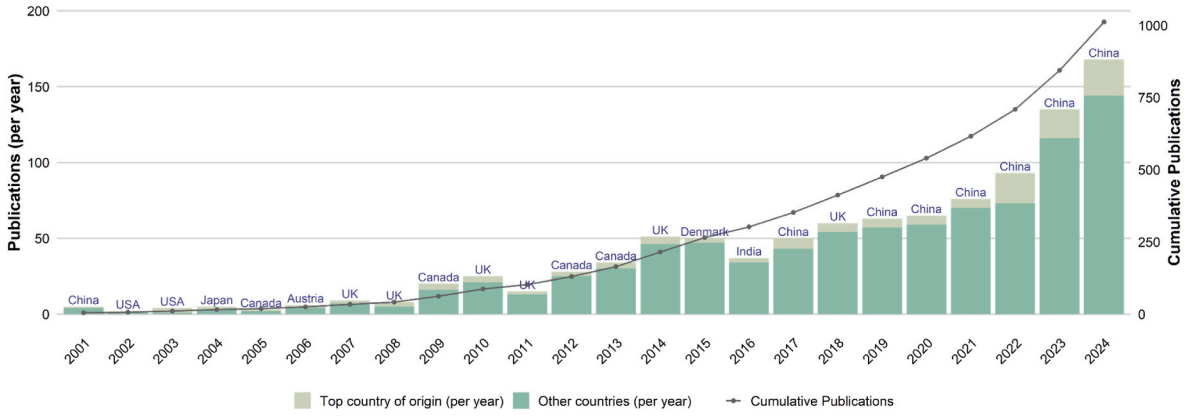


**Fig. 5.** Annual publications in energy security in energy systems, top country of origin per year, and cumulative total over time.

**Table 3**
Reviewed studies.

| Study region and citation | Energy focus | Time period | Strategy | Key Indicators |
|---|---|---|---|---|
| Global [32] | Fossil fuels, materials | 2000-2100 | Diversifying both fossil and metal supply chains, integrating critical minerals into energy planning, strengthening midstream processing capacities, and managing the material-intensive low-carbon transition. | - Supply concentration (HHI) of materials and fossil fuels<br>- Demand in the energy mix |
| Global (focus on Europe) [33] | LNG | 2040 | Diversifying LNG suppliers, relying on a mix of long-term and flexible short-term contracts, and maintaining domestic natural gas production with CCS. | - LNG import volume and costs<br>- Diversity of LNG suppliers<br>- Domestic supply |
| Global [34] | Biomass, electricity | 2020-2100 | Maximising domestic forest biomass production, participating in international trade, and using BECCS to reduce fossil fuel dependence. | - Biomass import share<br>- Diversification of the electricity mix |
| United Kingdom [35] | Biomass, electricity | 2100 | Maximising the net electricity balance of UK BECCS systems, optimising the choice of biomass feedstock, import regions, and value chain processes. Improving BECCS power plant efficiency and transport distances. | - Energy return on investment<br>- Electricity return on investment<br>- Net electricity balance<br>- Electricity pay-back time |
| United States [36] | Biomass | NA | Utilise sustainable wood bioenergy as a short-term, transitional "bridge" fuel, and provide dispatchable, on-demand power to complement intermittent renewables. | Impact on biodiversity, habitat, and water quality (qualitative study) |
| Global [37] | Fossil fuels | 1991-2017 | Diversifying suppliers and balancing import shares, maintaining stable long-term trade relationships, and investing in flexible energy infrastructure and contracts. | - Import dependency<br>- Diversification of suppliers |
| China, India, Japan, South Korea, and Taiwan [38] | LNG | 2002-2012 | Diversifying import sources across regional and non-regional suppliers, balancing long-term contracts with spot and short-term purchases, and engaging in international joint ventures. | - LNG imports<br>- Diversification of suppliers (HHI) |
| Global [39] | Oil | 2010 | Diversifying import sources across multiple regions, reducing dependence on any single exporter, building stable partnerships with key suppliers, and enhancing regional cooperation. | - Trade network |
| Global (focus on China) [40] | Fossil fuels, renewables, electricity | 1992-2012 | Diversify energy supply sources, expand reserves of oil and gas, improve electricity transmission efficiency, promote renewable energy and higher energy efficiency, maintain a stable political, regulatory, and economic environment, and support continuous investment in energy infrastructure. | - Security of energy supply<br>- Safety of energy utilisation<br>- Stability of the political-socioeconomic environment |
| Europe [41] | Fossil fuels | 2000-2100 | To reduce import dependency, lower oil and gas consumption, diversify the energy mix, enhance energy efficiency, and implement policies that internalise the costs of supply insecurity. | - Import dependency<br>- Commodity dependency<br>- Energy intensity |
| Global [20] | Fossil fuels, electricity | 2020-2100 | Support climate policies to cut fossil-fuel imports, lower exposure to oil and gas shocks, and boost energy-mix diversity and reliance on domestic resources. | - Energy trade and net import<br>- Diversity of energy sources |
| Global [42] | Fossil fuels, hydrogen, synthetic fuels, electricity, and biofuels | 2010-2100 | To reduce fossil fuel trade, expand domestic low-carbon energy (renewables and nuclear), improve energy efficiency, and increase the diversity and resilience of electricity and transport fuels, avoiding over-dependence on any single technology. | - Energy trade and net import<br>- Diversity of energy sources (HHI or SWDI)<br>- Energy intensity<br>- Geographic concentration of trade (HHI or SWDI) |
| Europe [43] | LNG | 2025-2030 | Diversify import partners, expand LNG capacity, reduce gas demand through efficiency and electrification, and accelerate the shift to renewables and heat-switching technologies. | - LNG trade and prices<br>- Diversity of energy sources<br>- Diversification of suppliers |
| Europe [44] | LNG | 2020-2050 | Energy efficiency, domestic production, and import diversification. | - Gas Imports<br>- Domestic Production<br>- Energy Efficiency |
| Europe [45] | Natural gas | NA | Diversify supply sources, strengthen energy resilience, eliminate Russian imports, and avoid long-term lock-ins in fossil-fuel infrastructure. | Price of gas and trade partnerships (qualitative study) |
| Europe [46] | LNG | NA | To establish an Energy Union to coordinate cross-border contracts, strengthen internal markets, and ensure solidarity among member states. | Security of gas supply and energy union (qualitative study) |
| Austria, Czech Republic, and Slovakia [47] | LNG | NA | States' perceptions of their own capabilities and vulnerabilities, not just their structural dependence, drive their stance toward the Energy Union. | Natural gas imports, transit, and consumption (qualitative study) |
| Lithuania and Russia [48] | Natural gas | NA | Diversification through LNG and structural interdependence that reduces supplier leverage. | Natural gas imports/exports, transit, and consumption (qualitative study) |
| Europe [49] | Fossil fuels, renewables | 2012-2021 | Diversify energy mix and combine traditional energy sources with renewables to ensure reliability. | - Total energy supply<br>- Final energy consumption |

(*continued on next page*)

**Table 3** (*continued*)

| Study region and citation | Energy focus | Time period | Strategy | Key Indicators |
|---|---|---|---|---|
| | | | | - Energy intensity<br>- Primary energy production |
| Sub-Saharan Africa [50] | Biomass, electricity | 2011-2019 | Expand renewable energy, modernise energy infrastructure, manage population growth, and promote regional collaboration to manage deforestation. | - Import dependency ratio<br>- Energy intensity<br>- Domestic production |
| Asian countries [51] | Fossil fuels, renewables | 1990-2014 | Diversify energy sources, improve efficiency, and transition gradually from fossil fuels. Promote regional cooperation and trade, with energy-rich countries supplying resources and energy-poor countries providing technology. | - Fossil fuel dependence<br>- $CO_2$ emissions intensity<br>- Import dependence<br>- Energy losses<br>- Low renewable energy share<br>- Inefficient energy use |
| Europe [52] | Nuclear, critical materials, electricity | 2010-2050 | A nuclear-intensive energy mix that reduces metal requirements, import dependence, and supply bottlenecks. | - Material Imports<br>- Material for energy capacity<br>- Material for the electricity sector |
| Global [9] | Nuclear | NA | Nuclear power and optimal energy mix decisions. | - Robustness<br>- Flexibility<br>- Redundancy<br>- Diversification<br>- Adaptability<br>- Interdependency |
| Brazil, Russia, India, China, and South Africa [53] | Fossil fuels, renewables | 2000-2020 | Renewables, energy efficiency, diversification, and cross-border renewable energy trade. | - Energy dependency<br>- Diversity in TPES<br>- Energy intensity<br>- Ratio of renewables for electricity generation<br>- Environmental sustainability |
| Europe [54] | Fossil fuels | 2010-2020 | Reduce import dependency, diversify energy sources, and improve energy efficiency. | - Energy productivity<br>- Energy import dependency<br>- Energy consumption<br>- Share of renewable energy |
| Europe [55] | Fossil fuels, electricity | 2000-2080 | Expand renewables, CCS, and prioritise energy efficiency to strengthen electricity system resilience. | - Import share<br>- Energy source diversity<br>- Energy intensity<br>- Import share for electricity production |
| Europe [8] | Fossil fuels, electricity | 2001-2100 | Climate policies, low-carbon power, energy efficiency, and securing gas supplies. | - Share of imports in TPES<br>- Import share for electricity production<br>- Energy intensity<br>- Diversity of sources in electricity production |
| China, Europe, India, and the United States [56] | Fossil fuels, electricity | 2010-2100 | To preserve domestic fossil fuel reserves as “buffers” and increase diversity in their energy mix, particularly in transport. As a result of the energy transition, a modest bioenergy trade may emerge as a partial substitute. | - Energy trade<br>- Import dependence<br>- Diversity of energy sources<br>- Diversity of sources in electricity production<br>- Diversity of sources in transport |
| OECD, Asia [57] | Fossil fuels | 2010-2100 | Energy efficiency alone is not effective. Diversification of energy suppliers and import sources is also necessary. | - Import dependency<br>- Diversity of suppliers |
| Sri Lanka, Thailand, and Vietnam [58] | Fossil fuels | 2007-2030 | Efficiency improvements, while essential, are not sufficient and must be complemented by shifts in the fuel mix and expanded investments in domestic or low-carbon alternatives. | - Import dependency<br>- Diversification of suppliers<br>- Energy intensity |
| Asian countries [59] | Fossil fuels, renewables | 2000-2100 | Large-scale investments in energy efficiency and clean energy. | - Import volume and share<br>- Diversity of energy sources |
| Europe [22] | Fossil fuels | 2025-2055 | Diversifying energy suppliers and transport routes, reducing dependence on imports, and shifting toward domestic resources. | - Import dependency<br>- Diversification of suppliers (HHI and SWDI) |
| Thailand, Cambodia, Myanmar, Vietnam, Laos [21] | Fossil fuels, renewables, nuclear | 2000-2035 | Diversifying energy supply portfolios and reducing reliance on any single fuel or external supplier. To leverage indigenous resources and expand regional electricity trade. | - Import dependency<br>- Diversity of energy sources |
| Laos and Thailand [12] | Fossil fuel, renewables, nuclear, hydropower | 2000-2035 | To use large-scale hydropower exports from Laos to diversify Thailand's energy mix and reduce its dependence on coal and other fossil imports. | - Import dependency<br>- Diversity of energy sources |

(*continued on next page*)

**Table 3** (*continued*)

| Study region and citation | Energy focus | Time period | Strategy | Key Indicators |
|---|---|---|---|---|
| Germany [60] | Natural gas | 2000-2023 | Leveraging AI adoption and stringent environmental policies, diversifying import routes, building strategic reserves, and accelerating the shift toward renewables and low-carbon technologies. | - Gas imports<br>- Artificial intelligence investment in energy efficiency |
| Italy [61] | Materials | 2025-2050 | Technology diversification in transport and power, alongside recycling initiatives and targeted international trade. | - Material supply risk<br>- Energy supply risk<br>- Internal reliability |
| United States [62] | Shale technology | 1973-2021 | Diversify energy sources, boost domestic shale, and invest in clean technologies. Strengthen storage, efficiency, and demand management. Secure import routes and upgrade cross-border infrastructure. | - Import dependency<br>- Diversity of energy sources |
| China [63] | Energy production and investment | 2013-2021 | Diversified suppliers, stress testing, and cybersecurity to safeguard production and investment in renewable energy. | - Primary energy consumption<br>- Vulnerability index |
| Finland, Estonia, Latvia, and Lithuania [64] | Electricity | 2050 | Diversify supply, scale renewables, and keep flexible backup. Expand interconnectors, energy storage, and reserves. Enable regional electricity trade. | Energy Security Coefficient (ESC) |
| China [65] | Fossil fuels | 2000-2018 | Enhancing domestic supply and strategic reserves, diversifying import routes, and boosting efficiency and environmental performance. | - Oil supply security<br>- Consumption security<br>- Ecological security |
| India [66] | Fossil fuels, renewables | 2002-2012 | Policy should expand renewables, secure oil and nuclear imports, and boost domestic gas. | - Availability<br>- Affordability<br>- Environmental Acceptability<br>- Efficiency |
| Tajikistan [67] | Electricity, hydropower | 1990-2014 | Renewable energy, energy efficiency, and community participation on a large scale. | Environmental constraints, limited generation capacity, costly energy imports, ageing infrastructure, weak transparency, poor regional cooperation, and inadequate financing (qualitative study) |
| Russia [68] | Fossil fuels | 1990-2018 | Diversifying exports towards Asia. | - Diversification of buyers<br>- Stability of energy production<br>- Economic feasibility of production/exports |
| Germany [69] | Fossil fuels, renewables, nuclear, electricity | 2020-2023 | Enhance coordination of cross-border electricity imports. | - Electricity imports<br>- Electricity demand<br>- Share of renewables |
| Germany [70] | Natural gas | 2015-2050 | Natural gas as a temporary bridge fuel, avoiding new lock-ins to gas technologies, and plan to repurpose existing pipelines for future carriers such as hydrogen. | - Import dependency<br>- Security of supply<br>- Affordability |
| United Kingdom [71] | Natural gas, electricity | 2025-2050 | Energy storage, coordinated grids, cross-carrier integration, and cross-border electricity trade planning. | - Gas and electricity performance<br>- Gas and electricity costs |
| Finland and Russia [72] | Fossil fuels, electricity | 2007-2040 | Fuel diversification, increased storage, and substitution of critical imports, self-sufficiency, and carbon-neutrality. | - Self-sufficiency<br>- Security of supply<br>- Affordability<br>- Environmental impact of supply |
| United Kingdom [73] | Fossil fuels, renewables, nuclear, electricity | 2018-2050 | Energy efficiency, storage, interconnection, and demand-side response. | - Import dependency<br>- Diversity of electricity sources<br>- Electricity costs<br>- Electricity flexibility<br>- Sustainability |
| Ireland [74] | Fossil fuels, renewables, nuclear | 2010-2050 | Energy efficiency and low-carbon fuel switching, particularly in transport and residential sectors. Expanding domestic renewable energy and flexible gas infrastructure. | - Import share<br>- Energy intensity<br>- Energy sources share |
| Pakistan [75] | Fossil fuels, renewables, nuclear | 2005-2050 | Expanding renewable energy to diversify the supply mix and cut import dependence. Carbon taxes promote efficient technologies and lower overall energy demand. | - Imports share<br>- Diversification of energy sources<br>- Diversification of energy demand<br>- Vulnerability index<br>- Energy intensity |
| United Kingdom [76] | Fossil fuels, renewables, nuclear | 2012 | High renewable penetration supported by grid-scale storage, interconnections, and dispatchable low-carbon generation, including CCS- | - Import dependency<br>- Diversification of energy sources |

(*continued on next page*)

**Table 3** (*continued*)

| Study region and citation | Energy focus | Time period | Strategy | Key Indicators |
|---|---|---|---|---|
| | | | equipped fossil plants, domestic energy production, and reduced import dependence. | |
| Pakistan [77] | Fossil fuels, renewables, nuclear | 2005-2050 | Diversification of energy sources, improved efficiency, and a shift in transport and industry toward domestic energy alternatives. | - Import dependency<br>- Diversification of energy sources<br>- Energy intensity |
| Japan [78] | Fossil fuels, renewables, nuclear, electricity | 2010-2030 | Maximising domestic renewables and natural gas while maintaining nuclear and hydro for a stable base load. A diversified energy mix and reliability are ensured via storage, backup systems, and decentralised generation. | - Import dependency<br>- Diversification of energy sources<br>- Electricity efficiency<br>- System stress |
| Nepal [79] | Hydropower | 2015-2050 | Electrification of transport using domestic hydropower to reduce fossil fuel imports, to diversify the energy mix, and to lower emissions. | - Import share<br>- Diversification of energy sources<br>- Oil consumption per capita |
| United States [80] | Shale technology, electricity | 2005 -2055 | Diversification of the energy mix, reserves, and flexible infrastructure, optimising domestic and imported resources. | - Diversity of electricity sources<br>- Electricity costs |
| United Kingdom [81] | Shale gas, renewables and nuclear energy | NA | Energy-source diversification. To assess how different energy-security concerns affect public support for these energy sources. | - Energy vulnerability<br>- Energy affordability<br>- Energy reliability<br>- Import dependency |
| Global [82] | Fossil fuels, renewables, end-use energy | NA | Energy efficiency, demand reduction, demand flexibility, electrification, behavioural and structural changes. | - Energy demand & flexibility<br>- Energy efficiency<br>- Energy costs |
| Global [83] | Materials | 1990–2060 | Strengthening energy security through diversified resource trade networks, increased recycling, and reduced reliance on critical minerals. | - Material demand<br>- Reduced reliance on material-intensive technologies |
| Europe [84] | Fossil fuels, renewables | 2019-2050 | Sufficiency and efficiency measures across all energy sectors. | - Import level<br>- Development of power grid and storage infrastructures |
| Denmark [85] | Fossil fuels, renewables | 1990-2011 | Commitment to energy efficiency, prolonged taxes on energy fuels, electricity, and carbon dioxide, and incentives for CHP and wind turbines. | - Energy import dependence<br>- Domestic energy production<br>- Renewable energy share<br>- Fossil-fuel use<br>- Energy self-sufficiency<br>- Electricity exports |
| Europe and Israel [86] | Fossil fuels, electricity | 2016 | Context-specific energy security strategies addressing import dependence, affordability, fossil-fuel reliance, and system reliability, alongside broader economic and social well-being. | - Import dependency<br>- Electricity costs<br>- Reliability<br>- Vulnerability<br>- Fossil fuel dependency |
| Global [87] | Materials | 1980–2060 | Renewable energy deployment, diversified international trade, lower material intensity of clean technologies, and increased recycling. | - Material intensity of energy technologies and recycling rates<br>- Share of renewable energy<br>- Resource-owning trading partners |
| Finland [88] | Final energy for all sectors | 2005-2015 | Energy efficiency improvements, energy consumption reductions due to energy intensity improvements. | - Import dependence<br>- Energy dependence<br>- Energy consumption |
| Sweden [89] | Biofuels | 2000-2030 | Domestic biofuel production, supply-chain diversification, integration of climate and energy-security policies. | - Import dependence<br>- Shannon diversity Index |
| Switzerland [90] | Electricity and Heating | 2022 and 2050 | Robust and secure imports, strategic reserves, domestic supply, flexibility. | - Self-Production<br>- Autonomy<br>- System Adequacy<br>- Self-Sufficiency |

Notes on abbreviations: AI = artificial intelligence; LNG = liquefied natural gas; BECCS = bioenergy with carbon capture and storage; CCS = carbon capture and storage; HHI = Herfindahl-Hirschman Index; SWDI = Shannon-Wiener Diversity Index; TPES = total primary energy supply.

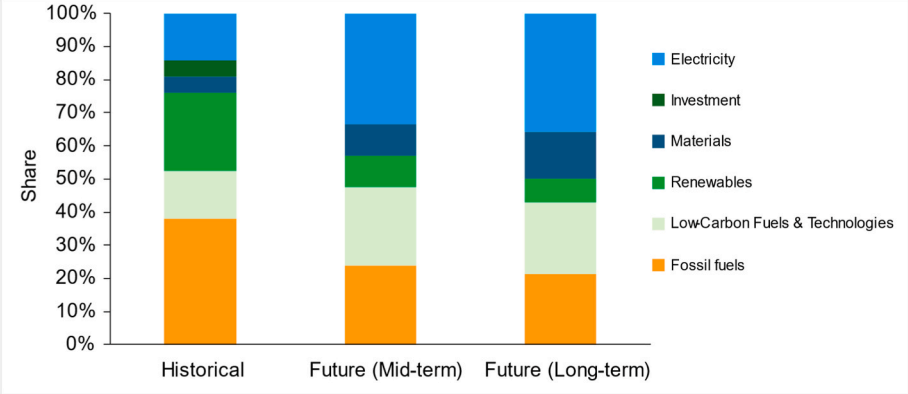


**Fig. 6.** Shifts in energy security focus in studies by timeframe.

### 3.2.1. *Energy focus and timeframe of the studies*

Fig. 6 illustrates a shift in the focus of energy security studies according to the time horizon analysed. Fossil fuels dominate historical and mid-term analyses (up to 2050) but decline in long-term studies beyond 2050, reflecting the increasing focus on the transition away from carbon-intensive energy sources rather than implying their complete phase-out. Fossil fuels continue to play a significant role in long-term energy scenarios, particularly given the uneven pace of the energy transition across countries and regions. Low-carbon fuels and technologies (e.g., Nuclear, BECCS, Biomass, Hydrogen, etc.) are mostly discussed in mid-term horizons, emphasising immediate decarbonisation priorities. Studies discussing different energy investment analyses reflect a current recommendation, based on historical trends. However, the relevance of materials and renewables maintains a stable representation across long-term scenarios where investment in infrastructure is assumed.

Electricity gains prominence in long-term studies (post-2050 and up to 2100), signalling a move from analysing individual energy sources toward the broader infrastructure, supply chains, and system dependencies that underpin the future energy mix. This trend highlights that discussions are no longer confined to traditional energy sources. Instead, vulnerabilities now emerge from the interconnected infrastructure, technology, and supply chains that underpin the future of energy systems.

### 3.2.2. *Energy security strategies*

*3.2.2.1. Emerging cross-border risks.* As the energy system evolves from fossil fuel dependence toward more interconnected, low-carbon infrastructures, the associated risks become increasingly cross-border and systemic rather than source-specific [91]. By reviewing how the focus of energy security has changed over time, alongside the strategies discussed in the studies, it is possible to trace how risks have evolved. These risks are not consistently measured across all studies, but they are often mentioned in the validation of the proposed solutions for improving energy security.

In the studies, three main categories of cross-border risks emerged: geopolitical, financial, and technological, which are summarised in Table 4. Geopolitical instability is a major exogenous driver of cross-border risks, as conflicts or diplomatic tensions can disrupt the trade of energy commodities, critical materials, and technologies [65,92,93]. For instance, the 2022 Russia-Ukraine conflict triggered global price spikes and supply shortages across European gas markets, illustrating how political shocks create market-wide vulnerabilities [45,46,49]. The recurring tensions between the United States and Iran provide another example of how geopolitical developments can generate cross-border risks. Disruptions to maritime transit through the Strait of Hormuz, a critical chokepoint for global oil and LNG flows, could affect energy markets well beyond the immediate region [94]. The attacks on commercial shipping in the Red Sea offer a further example, as disruptions to maritime trade through the Bab el-Mandeb Strait have forced energy carriers to reroute, creating additional risks for global oil and LNG flows [95]. These cases also highlight the importance of import dependence as a key dimension of cross-border risks, particularly where countries rely heavily on unstable suppliers or vulnerable trade routes. Under such circumstances, most studies in this review advocate strategies that prioritise supply diversification to reduce exposure to geopolitical risk.

The energy transition introduces cross-border financial risks through changes in the value, financing, and investment in energy infrastructure, as well as through energy-price dynamics. Two mechanisms are particularly relevant. First, the early retirement or declining utilisation of fossil and gas infrastructure can create exposure by reducing the value of existing assets before their economic lifetime, known as stranded assets, while increasing the cost of replacing this capacity, known as lock-in cost [70]. These costs can extend across borders through the foreign ownership, financing, and interconnected operations of energy companies [63]. Thus, investment flows in energy infrastructure can be constrained. Second, because cross-border energy companies use instruments such as commodity derivatives to manage price risk, this practice creates linkages across energy and financial markets, providing potential channels for financial interdependence and spread of risk [96].

Technological risks in the energy sector arise when barriers constrain international knowledge spillovers that are essential for innovation and cost reductions. Limited access to new energy technologies and expertise slows learning, increases costs, and delays the deployment of low-carbon energy options, particularly renewables that rely on cumulative global innovation [93,97], [98]. As a result, energy systems become more rigid, more expensive, and more vulnerable to technological lock-in, depending on foreign supply and investment to access innovations in energy technologies and infrastructure [53].

Although Table 4 presents three risk categories, the reviewed studies

**Table 4**
Cross-border risks.

| Risk | Cross-border element discussed |
|---|---|
| Geopolitical | Disruptions to international trade of energy commodities, critical materials, and technologies caused by geopolitical instability, conflicts, and diplomatic tensions; exposure to global price shocks and supply shortages. |
| Financial | Cross-border financial exposure from stranded fossil-fuel assets, lock-in costs, and consequent constraints on investment flows; and financial-market interdependence and spillovers through which energy price and market shocks propagate across economies. |
| Technological | Dependence on international knowledge spillovers, foreign technology supply, and cross-border investment for innovation, cost reductions, and deployment of low-carbon energy technologies; risk of technological lock-in. |

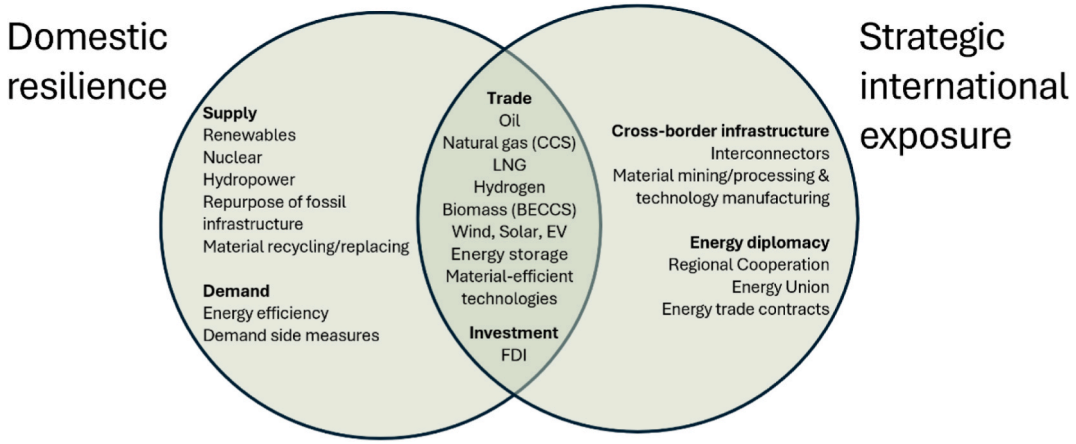


**Fig. 7.** Solutions to cross-border risks.

indicate that geopolitical, financial, and technological risks are closely interconnected and can compound one another. LNG import diversification can reduce geopolitical exposure to unstable suppliers but increase financial and technological risks through the cross-border investment and infrastructure required for LNG import and processing [33,38]. Similarly, reducing dependence on particular critical-material suppliers can lower geopolitical exposure while increasing financial exposure through higher costs and investment requirements and constraining access to dependent technologies [61]. Cross-border electricity interconnection can reduce geopolitical and financial risks by pooling supply across larger markets, but also increase technological and financial exposure through continued infrastructure investment and technology transfer [69,73]. Thus, reducing one form of exposure may increase another, and assessing risks separately may underestimate the overall vulnerability of interconnected energy systems.

*3.2.2.2. Solutions.* In the studies, solutions to cross-border risks are generally grouped into two main types: domestic measures, which focus on strengthening domestic capacity and resilience, and international measures, which involve cooperation with other countries. These are illustrated in Fig. 7.

To enhance domestic resilience, domestic solutions focus on both supply- and demand-side measures. On the supply side, strategies include maintaining nuclear facilities, investing in renewables, developing hydropower, and expanding biomass production to reduce import reliance and diversify electricity generation [34], [35], [36], [50], [52], [66], [73], [75], [77], [78], [79]. Studies also showed that existing fossil fuel infrastructure can be repurposed to support domestic energy production of clean alternative fuels, improving resilience and reducing dependency on imports [70]. Additionally, recycling materials for clean energy technologies is part of domestic strategies aimed at reducing reliance on concentrated supply chains and supporting the energy transition [61]. On the demand side, energy efficiency and consumption control, shaped by energy policy and population management, are among the discussed measures for enhancing energy security at the domestic level [41], [43], [44], [50], [54], [67], [74]. AI technologies also play a role in the demand-side measures by optimising energy consumption [60].

In trade, the focus is on the energy sources and technologies that can be imported and implemented domestically. Although oil imports are expected to decline as energy systems transition, they remain an important component of the current energy mix [25], [65], [80]. In fact, data show that fossil fuel imports continue to grow alongside renewables [10]. Studies modelling future scenarios, however, forecast a gradual reduction in fossil fuels [20].

Natural gas trade has often been considered a strategic lower-emission supply option, particularly when combined with carbon capture and storage (CCS). However, the war in Ukraine exposed the vulnerability of natural gas markets to geopolitical disruptions, contributing to sharp price increases and heightened market volatility. In this context, studies suggest that LNG can serve as a short-term alternative to conventional natural gas imports, helping to mitigate uncertainty, while hydrogen offers opportunities to diversify fuel imports away from fossil fuels [42], [71]. Biofuels, such as biomass, in some studies combined with CCS (BECCS), are also discussed as increasing alternatives to diversify electricity generation [34], [35], [56].

Trade in wind, solar, electric vehicles (EVs), and energy storage technologies is discussed as crucial to build domestic clean infrastructure and improve energy security [76]. However, concerns related to critical material supply chains introduce new dependencies that may affect their deployment and scalability [32], [52]. While these constraints do not diminish the central role of these clean technologies in the transition, they highlight the importance of diversification and technological innovation, such as finding less material-intensive technologies [52].

Regarding investment, many less-developed, resource-rich countries with growing energy demand remain vulnerable in future energy transition scenarios if domestic renewable infrastructure development is limited. Consequently, foreign direct investment (FDI) plays a crucial role in building domestic clean energy capacity, accelerating the transition, and enhancing energy security [50], [53]. In Europe, foreign investment has supported solar and wind development [72]. However, the strategic importance of energy infrastructure and technologies increasingly makes such investments subject to national security considerations.

Strategic international exposure is a recommendation found in the studies that advocates for considerations of long-term connections with other countries that are strategically contributing to domestic resilience. In terms of cross-border infrastructure, cross-border electricity interconnectors provide solutions for countries that are geographically close and able to invest in the necessary infrastructure [64]. The interconnection supports diversification of electricity generation by allowing countries to access a wider range of generation sources across a regional system, reducing reliance on domestic generation capacity. However, investment in mining and manufacturing capacities is argued to be a strategic solution for countries with geological potential to protect energy systems from a volatile mining market [32]. But this is mainly seen as an intercountry solution, as mining, processing, and manufacturing are interdependent processes in the energy industry and are usually dispersed across different geographies.

Energy diplomacy solutions are found in instances of integrating energy systems, fostering interdependence with strategic partners, or adjusting trade agreements and supporting decoupling from partners

that are no longer viable. For example, in Asia, increased regional electricity trade demonstrates how renewable generation and grid interconnection can collectively enhance energy security while reducing carbon intensity [21]. Similarly, the diversification of fossil fuel exports, such as Russia's strategic pivot toward Asian markets, reduces over-reliance on traditional buyers, extends its energy diplomacy to this new market, and mitigates export declines [68]. Political initiatives, such as the Energy Union in the EU, illustrate how coordinated policies within a multilateral framework can create a common energy market, promoting solidarity and stability [47]. Beyond diversification, an Energy Union can reduce vulnerability by changing how interdependence is managed. Cooperative mechanisms can pool bargaining power, distribute supply-disruption impacts, coordinate infrastructure and reserves, and establish common rules for trade and market access [46], [47]. The objective is not to eliminate energy dependence, inherent to interconnected systems, but to reduce its potential for political or economic exploitation [51]. Additionally, adjustments in trade contract lengths can serve as a tactical tool to protect energy supply amid shifts in global and regional trade networks [33], [37].

Across the sample, energy security is shaped by resource endowment but is not reducible to it. In resource-rich settings, studies place greater emphasis on domestic production and the use of indigenous resources as strategic buffers [34], [35], [56], [62], [80], whereas more import-dependent systems emphasise diversification, reserves and substitution [37], [41], [43], [54], [64], [71], [86]. Across both settings, however, security increasingly depends on the ability to adapt to disruptions through flexible infrastructure, efficiency, interconnection, diversified energy sources, trade partners and supply chains [82], [83], [85]. The studies also suggest that security is not achieved by eliminating interdependence, but by managing it via combined domestic resilience and strategic international exposure solutions. As the energy transition progresses, this logic extends beyond fuels to the materials, technologies and infrastructure required to build and operate low-carbon energy systems [32], [52], [61], [83], [87].

*3.2.2.3. Geographic patterns in solutions.* Geography can either limit or expand the range of domestic solutions, as countries and energy systems differ in their access to natural resources, physical infrastructure, and technology [48], [99]. A geographic pattern is visible across the solutions discussed above, and it corroborates the bibliometric trend identified in Figs. 3 and 5. The growing volume of Chinese-led publications is accompanied by a distinct approach to the strategies these studies propose. Chinese-focused studies in our systematic review sample combine supply-side diversification and strategic reserves with continued domestic oil exploration and production, framing partnerships such as the Belt and Road Initiative as a mechanism for extending state-coordinated investment into overseas energy infrastructure and supply chains [40], [65].

The Western cases in our sample emphasise a different approach. Studies focusing on Germany, the United States, and the Baltic states primarily emphasise market-based diversification, decentralised private investment, and regulatory or pricing incentives [60], [62], [64]. However, these approaches also provide only partial gains, reducing exposure in some areas while leaving other vulnerabilities unresolved or dependent on effective implementation. This contrast suggests that the two broader approaches, state-coordinated investment abroad versus market-based diversification, carry challenges specific to the mechanism relied upon.

*3.2.2.4. Challenges to solutions.* While the reviewed studies discuss a variety of solutions tailored to specific energy security strategies, many results still indicate that future pathways may still entail significant vulnerabilities [21], [39], [42]. This suggests that energy security could deteriorate over time despite the implementation of the proposed solutions. Therefore, we critically analyse these findings by examining the specific constraints associated with each type of solution and situating our results within a broader body of literature, including studies not covered in the initial literature review and those reporting contrasting findings.

**Domestic supply.** Reliance on domestic natural gas as a bridging fuel may reduce exposure to external supply disruptions in the short term, but can create carbon lock-in and stranded-asset risks over the longer term [36], [70]. Also, nuclear power, although contributing to domestic energy supply, can be vulnerable to prolonged dry conditions that reduce cooling-water availability and constrain plant operation [100], [101]. Such climate-related constraints illustrate that domestic generation is not necessarily more secure. Similarly, domestic solutions such as materials recycling may not scale at the pace required by the energy transition to compensate for sudden disruptions in foreign material or technology supply [102], [103], [104]. As demand for energy materials increases, limited recycling capacity can therefore leave energy systems exposed to technological cross-border risks. These limitations can extend to circular economy practices such as waste and biomass. While these practices can strengthen energy security by reducing dependence on imported fossil fuels and resources, their contribution is similarly constrained by resource availability, technological capacity, infrastructure, and investment requirements [104], [105], [106], [107]. These limitations suggest that circular solutions should complement, rather than substitute for, diversified energy and material supply strategies.

**Domestic demand**. The key challenge is balancing demand reduction with the need to expand and diversify supply as energy needs evolve. Evidence from global and regional modelling indicates that demand-side measures alone may not be sufficient to ensure long-term energy security, contrary to the objectives pursued by some industrialized countries [57], [58], [59]. This suggests that, at the country level, demand reduction alone may not eliminate dependence on imported oil and gas, highlighting the need to complement demand-side measures with supply-side strategies [57]. As the energy transition progresses, this trade-off requires increasingly complex strategies to manage volatile markets and geopolitical dynamics.

**International trade**. Heavy reliance on imported technologies or fuels can shift dependency from one technology or supplier to another [21], [39], [42], rather than improving overall energy security, as existing vulnerabilities may be transferred rather than eliminated. The EU's recent pivot from Russian pipeline gas to US-sourced LNG illustrates this dynamic. While intended to diversify supply and strengthen energy security, the shift has also created a new form of dependence. Concerns over potential US export curtailments, whether resulting from domestic pressures or geopolitical conflicts, highlight how reliance on US LNG could itself introduce new vulnerabilities into the EU's energy system [108], [109], [110]. The literature therefore suggests that managing such risks requires a portfolio of complementary measures [111], including demand reduction and flexibility, clean energy transition [57], [112], [113], resilient and interconnected infrastructure [114], and balanced trade partners [39], [115].

A similar dynamic is emerging in the transition toward renewable energy, where reduced dependence on imported fossil fuels can be accompanied by greater dependence on imported critical materials and technologies. Recent evidence shows that although overall trade risks decline in most countries under net-zero scenarios as fossil-fuel dependence decreases, trade risks associated with electricity and transport systems increase in many countries that become more dependent on imported materials [52], [61], [116]. This suggests that the energy transition can redistribute, rather than eliminate, trade-related vulnerabilities. Moreover, increasing renewable energy deployment does not necessarily translate into greater energy security where the supply of critical raw materials remains exposed to external disruptions [117].

Greater interdependence in new trade relations can also create spillover effects, whereby disruptions affecting one supplier or market propagate through connected trade networks [39]. Strategic alliances

and diversified trade relationships can therefore help mitigate exposure to trade disruptions. As presented earlier, however, domestic supply strategies can also reduce external dependence while introducing their own vulnerabilities (e.g., limited capacity, resources and infrastructure), meaning that neither domestic production nor international trade can be considered a standalone solution to the emerging cross-border risks.

**International investment**. Studies in our sample identify two distinct approaches to international investment, each presenting different energy security challenges. In state-led investment models, such as those examined in the Chinese context, coordinated investment and international cooperation can strengthen access to resources and production capacity. However, it can also create systemic vulnerabilities, whereby shocks affecting individual firms or sectors propagate through the wider energy system. Evidence from Chinese energy firms shows that systemic risk spillovers can propagate shocks through the energy system, reducing energy production and investment and consequently weakening both short- and long-term energy security [63]. These effects are particularly pronounced when shocks originate in state-owned firms, reflecting the wider systemic consequences of concentrated state involvement in the energy sector.

In market-based investment models, the main challenge relates to the dependence of investment decisions on the policy environment. Supportive climate and energy policies can attract foreign investment and accelerate the deployment of renewable technologies, but firms may also respond to changes in policy support by redirecting investment towards more favourable jurisdictions. Evidence from the European solar industry shows that adverse policy changes can reduce firms' confidence in similar policy frameworks elsewhere, making policy stability an important condition for sustaining foreign investment [118]. Investment screening can therefore shape cross-border investment in areas including energy infrastructure, renewable generation, and battery technologies, illustrating that the contribution of international investment to energy security depends not only on capital availability but also on the international cooperative frameworks and regulatory conditions governing its deployment against financial cross-border risks [119].

**Cross-border infrastructure.** The main challenges associated with cross-border infrastructure relate to developing the power and electricity infrastructure required to support regional electricity trade [73], [120]. Such investment requires countries to align technical standards and transmission requirements, while also coordinating investment in infrastructure that spans national borders. These challenges become particularly important in the context of emerging mineral and materials value chains, where mineral extraction, processing, manufacturing, and end-use activities are often distributed across different countries. Developing these value chains therefore requires coordinated investment in transport networks, ports, and other enabling infrastructure that connect resource-producing regions with processing and manufacturing centres, a context where technological, geopolitical, and financial cross-border risks are compounded. However, international coordination can be difficult where countries have different regulatory frameworks, investment capacities, and development priorities [121].

**Energy diplomacy.** The main challenge of energy diplomacy is managing interdependence so that cooperation and new strategic alliances do not create new asymmetries of power and dependence. Russia's pivot towards Asian markets, for example, reduced its dependence on European buyers while creating new dependencies on Asian markets and infrastructure [120]. Multilateral frameworks, such as an Energy Union, can mitigate these risks by maintaining more symmetrical exit costs and enabling states to pool bargaining power [122]. Their effectiveness is nevertheless limited when states or regional blocs use growing interdependence to accumulate power or pursue hegemonic positions [122], [123]. Energy diplomacy therefore remains subject to geopolitical risk.

#### 3.2.3. Key indicators

The reviewed studies evaluate energy security primarily through four types of indicators. In order of frequency, these are *supply and demand* (46%), *supply-only* (28%), *cost-related* (17%), and *environmental impact* (9%) indicators. The strong reliance on supply–demand measures reflects a continued focus on adequacy and balance, but also a classical framing of security. In this view, an energy system is considered secure when it can reliably supply energy to meet demand and effectively manage or control that demand when necessary [1]. The significant share of supply-only studies shows energy security is still largely viewed through the lens of fuel sourcing, which risks overlooking demand-side dynamics and efficiency improvements [8], [55], [59]. Similarly, the limited attention to costs and affordability further indicates that socio-economic aspects remain underexplored for security assessment within energy systems analyses, despite geopolitical changes influencing both material availability and price stability [124], [125]. This gap may reflect the economic focus of market fluctuation analyses, which are not consistently integrated into energy security studies, highlighting a key limitation of current frameworks. Finally, environmental indicators are the least developed domain, highlighting a conceptual gap at a time when decarbonisation is redefining what constitutes energy security. While environmental targets are increasingly embedded in policy and modelling frameworks, their integration into energy security measures remains underdeveloped.

## 4. Conclusion and policy implications

This review addressed three research questions. On the evolution of energy security framing (RQ1), the bibliometric analysis shows that energy security has broadened over four decades, moving since 2016 beyond the geography of resources toward the geography of materials, manufacturing capacity, and technological innovation, reflecting the growing salience of cross-border risk, alongside a growing prominence of Chinese-led research. On emerging cross-border risks (RQ2), the systematic review identifies geopolitical, financial, and technological risks as closely interconnected, spanning technology access, the financial exposure of fossil-fuel phase-out, and the geopolitics of energy trade and investment in the energy transition. It also reveals differentiated approaches to addressing these risks, with Chinese-focused studies emphasising state-coordinated investment, diversification, and strategic reserves, while Western studies more often emphasise market-based diversification and private investment. On effective energy security strategies (RQ3), we found that no isolated solution eliminates risk. Overreliance on one supplier or technology shifts rather than removes exposure, demand-side measures are insufficient in isolation, and short-term bridging solutions can introduce long-term vulnerabilities such as carbon lock-in.

This study's main contribution is to redefine energy security in the clean energy transition as the governance of (inter)dependence rather than its reduction. As clean energy systems become increasingly interconnected across borders, security cannot be achieved simply by reducing external reliance. Instead, it depends on how states manage, diversify, and govern cross-border interdependence to capture the benefits of trade while limiting exposure to emerging risks. This shifts energy security from a paradigm of self-sufficiency to one of managed interdependence and provides a new basis for assessing how much and with whom states should cooperate in increasingly interdependent clean energy markets.

For policymakers, this review supports context-specific action. Countries with limited domestic resources may benefit more from strategic energy diplomacy and long-term supply contracts than from import reduction targets. Resource-rich countries or countries with high renewable potential may instead prioritise domestic capacity building and use strategic partnerships to support this expansion. As shown in this study, EU members can draw on regional interconnection and frameworks such as the Energy Union to coordinate investments, while countries in the Global South may rely more on bilateral partnerships and infrastructure investment. International institutions such as the IEA

and IRENA can further facilitate this approach through data transparency, support for managing supply disruptions, and support for technology transfer to countries that lack the domestic capacity to develop these capabilities themselves.

This study is not free of limitations. The bibliometric findings should be read with caution, reflecting one plausible reading of the corpus shaped by the clustering method chosen. Alternative approaches, such as Latent Dirichlet Allocation, could surface different groupings. Reliance on the keyword co-occurrence method may also overlook nuanced discussion and cannot capture how the transition unfolds unevenly across countries, a gap in parts addressed through the qualitative systematic review. Within the systematic review, the methodological choice to focus on studies that explicitly assess both exposure and resilience provides a consistent analytical basis but may exclude research using alternative conceptualisations of energy security and limit cross-country comparison. Finally, this review considers biomass production and the recycling of materials and critical minerals as domestic supply solutions that can strengthen energy security, while recognising that other relevant circular economy strategies may not be fully captured in the reviewed literature. Despite these limitations, the circular economy represents an important complementary strategy for energy security, warranting further investigation in future research.

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## Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used ChatGPT for improving the language, grammar, clarity, and readability of the manuscript. The author(s) reviewed and edited the output as needed and take full responsibility for the content of the published article.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2026.102394.

## Data availability

No data was used for the research described in the article.

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